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IGNITION OF AIRCRAFT FLUIDS BY HOT SURFACES UNDER DYNAMIC CONDITIONS

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13. ABSTRACT

Data are presented on the ignition characteristics of various aircraft fluids under conditions in which they impinge upon a hot surface in the presence of air flow similar to that possible in an aircraft enclosure. The fluids included two jet fuels (JP-4 and JP-8), two hydraulic fluids (MIL-H-5606 and MIL-H-83282), and an engine oil (MIL-L-7808). Ignition temperatures were determined with heated cylindrical steel targets which varied from one to four inches in diameter and from 12 to 24 inches in length; a flat target which measured 3-5/8 inches by 12 inches was also used. Generally, the ignition temperatures decreased with an increase in target diameter or surface area and increased with increasing air velocity. The results were lower with the use of preheated air (350°F), particularly for the fluids of low volatility. At all test conditions, the ignition temperatures of the fluids were noticeably higher than their minimum autoignition temperatures which are determined in uniformly heated vessels. The variation of ignition temperature with target surface area was more sensitive to changes of diameter than length.

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DYNAMIC CONDITIONS

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FOREWORD

This report was prepared by the Pittsburgh Mining and Safety Research Center of the U. S. Bureau of Mines under USAF Contract No. F33615-69-M-5002. The contract was initiated under Project No. 3048, Task No. 304807 "Aerospace Vehicle Hazard Protection". It was administered under the direction of the Air Force Aero Propulsion Laboratory, with Mr. R. G. Clodfelter (AFAPL/SFH) acting as project engineer.

This report is a summary of the work recently completed as part of this current contract during the period 1 January 1969 to 31 August 1971. This report was submitted by the autnors October 8, 1971.

Dr. Robert W. Van Dolah was the administrator for the U. S. Bureau of Mines and Messrs. A. Strasser, N. C. Waters, J. M. Kuchta, J. Grumer and V. M. Rowe actively participated in this project at the U. S. Bureau of Mines Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa.

This technical report has been reviewed and is approved.

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ABSTRACT

Data are presented on the ignition characteristics of various aircraft fluids under conditions in which they impinge upon a hot surface in the presence of air flow similar to that possible in an aircraft enclosure. The fluids included two jet fuels (JP-4 and JP-8), two hydraulic fluids (MIL-H-5606 and MIL-H-83282), and an engine oil (MIL-L-7808). Ignition temperatures were determined with heated cylindrical steel targets which varied from one to four inches in diameter and from 12 to 24 inches in length; a flat target which measured 3-5/8 inches by 12 inches was also used. Generally, the ignition temperatures decreased with an increase in target diameter or surface area and increased with increasing air velocity. The results were lower with the use of preheated air (350°F), particularly for the fluids of low volatility. At all test conditions, the ignition temperatures of the fluids were noticeably higher than their minimum autoignition temperatures which are determined in uniformly heated vessels. The variation of ignition temperature with target surface area was more sensitive to changes of diameter than length.

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INTRODUCTION

With increased performance requirements for advanced aircraft, potential fire and explosion problems are more difficult to cope with because of the increased hazard resulting from higher flight environmental temperatures. The high surface temperatures associated with engine compartments and bleed-air ducts are a major concern because of the ignition hazard in the event of a fuel line failure. To define the hot surface ignition hazard, the ignition temperature of the combustible fluid must be known as a function of the heat source dimensions under static and flow conditions. The noticeable effect of heat source dimensions on the ignition temperatures of the JP-6 fuel and the MIL-L-7808 engine oil was defined in earlier work (Refs 3, 5), where small heat sources were used with premixed vapor-air mixtures at near-stagnant conditions. The present investigation was undertaken to define the ignition hazard associated with impingement of liquid streams of the aircraft fluids onto relatively large heated steel targets in flowing air. Ignition temperature data were obtained at various air velocities (<10 ft/sec) with cylindrical and rectangular targets for the JP-4 and JP-8 jet fuels, the MIL-L-7808 engine oil, and the MIL-H-5606 and MIL-H-83282 hydraulic fluids.

This work was conducted as part of the Air Force sponsored contract F33615-69-M-5002 "Investigation of Flight Vehicle Materials Fire Characteristics and Fire and Explosion Suppression Techniques". Other work performed under this program includes ignition inhibition and fire suppression studies with halogenated hydrocarbons, which will be described in a later report.

EXPERIMENTAL APPARATUS AND PROCEDURE

1. Flow Apparatus

The ignition temperature experiments were performed by injecting the aircraft fluids onto heated steel targets under various air flow conditions in an 8-inch diameter tube. Figure 1 shows a sketch of the flow tube which consisted of a 6-foot long by 8-inch diameter pipe, modified for access to the target and fitted with windows for observation. The tube also had 1-inch pipe openings at 3-inch intervals along the top and bottom center line, which were used for mounting targets, thermocouples, and other equipment as necessary. The top of the flow tube had a removable section to provide access to the inside. A 4-inch diameter pipe connected the upstream end of the tube to a large capacity, 1400 scfm air compressor. Eight feet of this pipe were covered with asbestos tape and wound with Nichrome wire for heating the air. In addition, a 24-inch long by 2-inch diameter cylindrical heater was mounted axially in the downstream end of the pipe. With this heater, which consisted of two semi-cylindrical elements (220 volt) cemented together, it was possible to heat the air to 350°F at 200 scfm, the highest rate of flow used.

Air velocity was generally calculated from the volumetric flow and the annular cross-sectional area produced by a given target. A hot wire anemometer was used to check the average air velocity values, which were calculated from flows indicated by orifice meter readings. This technique measured the velocities in the annular space between a centrally located target (2 inches diameter by 9 inches long) and the inside wall of the flow tube. The velocities near the middle of the annular space were higher than those near the walls. Turbulence at the high velocity points was about 20 percent and ranged downward to 2.5 percent at the lowest points. Table I compares the measured local air velocities that were obtained at upstream, middle, and downstream positions in the annulus for three different flow conditions. The calculated average velocity values are representative of the actual velocities measured near the target. Therefore, the air velocity values used in the experiments were calculated on the basis of the air flow measurements, as determined by the orifice meter.

Fuel was injected through an orifice in a 1/8-inch pipe cap which was threaded to an assembly directly above the center of the target. Orifice holes were either 0.025-inch or 0.040-inch diameter. The assembly was connected to a hand-operated, quick-opening valve which was connected in series with a flowmeter and a fuel reservoir pressurized with nitrogen from 10 to 250 psig. The orifice assembly was surrounded with a water jacket to prevent overheating of the flammable fluid prior to injection onto the target. Rate of fluid flow was controlled by varying the reservoir pressure or the orifice diameter. Since one to two seconds were required for the flowmeter to reach a steady state, the fluid flow duration was standardized at 3 seconds unless ignition occurred earlier.

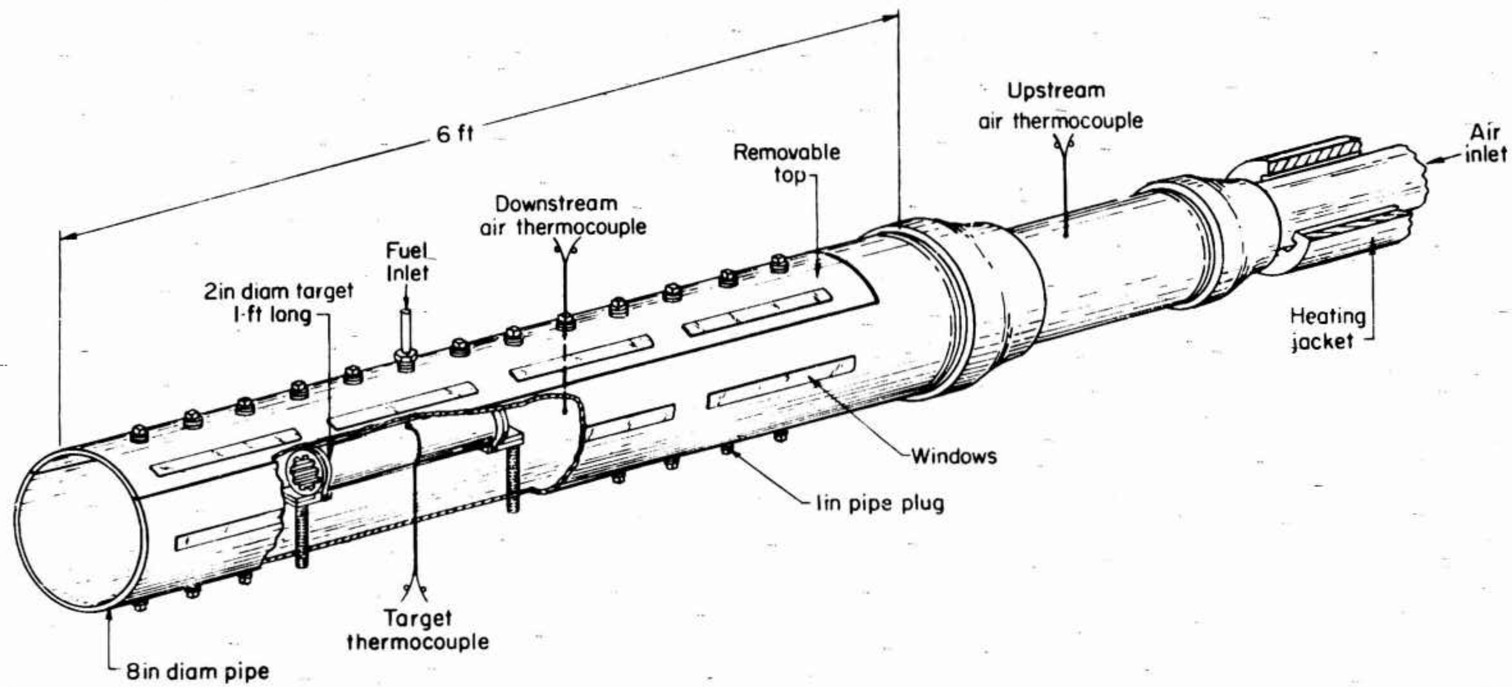


FIGURE 1. - Ignition flow tube with 2-inch diameter by 12-inch long target mounted in position.

TABLE I. - Comparison of Calculated and Measured Air Velocities at Various Locations in the Annular Space Between a 2-inch Diameter Target and the Wall of the 8-inch Diameter Flow Tube.

Distance from Top Wall of Flow Tube, inches	Axial position of probe	Measured Local Air Velocity, ft/sec		
	Calculated Average Air Velocity, ft/sec	0.53	0.76	1.51
0 (wall)	Upstream[1/]	<.26	.26	1.0
.4	"	<.26	.43	1.0
.8	"	<.26	.60	1.25
1.2	"	<.26	.60	1.4
1.6	"	.26	.60	1.55
2.0	"	.43	.76	1.55
2.4	"	.60	.76	1.55
2.8	"	.26	.76	1.25
0 (wall)	Middle[2/]	.43	.26	1.13
.4	"	.43	.43	1.4
.8	"	.43	.43	1.4
1.2	"	.60	.76	1.55
1.6	"	.43	.76	1.55
2.0	"	.43	.76	1.55
2.4	"	.43	.76	1.55
2.8	"	.43	.60	1.4
0 (wall)	Downstream[3/]	.36	.43	1.26
.4	"	.36	.43	1.38
.8	"	.43	.60	1.38
1.2	"	.53	.60	1.55
1.6	"	.53	.76	1.55
2.0	"	.53	.76	1.55
2.4	"	.53	.60	1.38
2.8	"	.53	.43	1.26

1/ Probe 5/8-inch from upstream end of target.
2/ Probe directly above center of target.
3/ Probe 5/8-inch from downstream end of target.

2. Heated Targets

The aircraft fluids were injected onto electrically heated steel targets that were axially mounted in the 8-inch diameter flow tube. Figure 2 shows the six different targets that were used in these experiments. Target dimensions were as follows:

(A) Cylindrical targets - 24 inches long; 1 and 2-inch diameter
(B) Cylindrical targets - 12 inches long; 1, 2 and 4-inch diameter
(C) Flat rectangular target - 12 inches long by 3-5/8 inches wide

A 3-inch diameter by 12-inch long target was also used for some experiments, but the results are not included because of anomalies from nonuniform temperatures along the target. Where temperatures were uniform, the ignition temperature data were similar to those for the 4-inch diameter target.

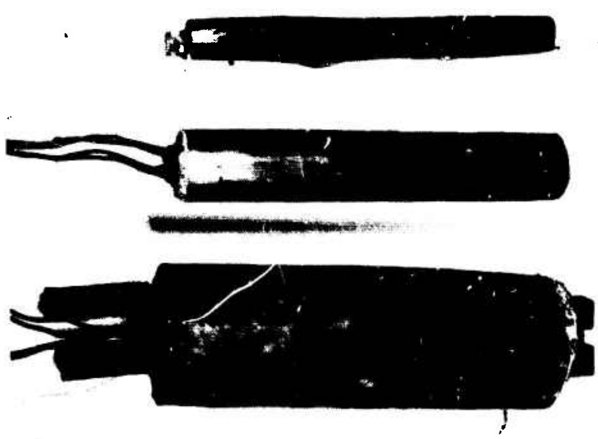
The targets were constructed of 0.010-inch thick stainless steel sheet, surrounding a ceramic form. The ends of the stainless steel sheet were brazed to relatively massive pole pieces which were connected to a low voltage, high current transformer; primary voltage was controlled by a 220-volt variable transformer. With this arrangement, the 1-inch diameter targets could be uniformly heated to 1200°F with heating currents up to 500 amperes. However, for the larger diameter targets and for the flat target, it was necessary to use a supplementary heating mode in order to obtain uniform target surface temperatures. The supplementary heating was provided by the use of ceramic forms equipped with resistance heating elements of 2000 watts or less.

The target temperature was normally monitored by a Chromel-Alumel thermocouple located immediately below the point at which the flammable fluid impinged on the target. The surface temperatures were fairly uniform, with the exception of those near the target ends, particularly if only one mode of heating was used. By using both internal and external heating, the target temperature was equalized over most of its area. Uniformity was examined in two ways. The first was simply to heat the target in quiescent air and compare the thermocouple reading at the midpoint with the melting point of a Tempilstik at various locations on the target surface. To verify uniformity of temperature under flow conditions, three thermocouples were imbedded in the target -- one at the center and the other two at points along the center line two inches from each end. With optimum heating and 3 ft/sec air velocity, a maximum temperature difference of 30°F was observed between various points on the target when the nominal temperature was between 960° and 1260°F, as indicated by the center thermocouple.

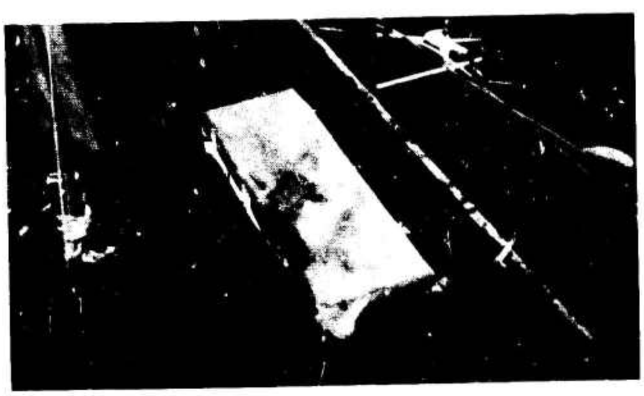
3. Procedure

To determine the ignition temperatures, the target was first heated to an arbitrary temperature under the desired air flow condition and the

A. Cylindrical Targets, 1- and 2-inch diameter by 24 inches long.



B. Cylindrical Targets, 1-, 2-, and 4-inch diameter by 12 inches long.



C. Rectangular Target, 3-5/8-inch by 12-inch, mounted horizontally in 8-inch diameter flow tube.

FIGURE 2. - Electrically heated stainless steel targets used in ignition temperature experiments.

fluid was injected at a predetermined rate for periods up to 3 seconds. Since an air velocity of 1 ft/sec was calculated to give a maximum fuel dwell time (contact time) of 1 second around the 12-inch long heated target, the 3-second flow period was considered adequate for the present experiments. This maximum fuel flow period was also used in the corresponding runs in quiescent air to permit data comparisons under the same fuel injection conditions. The variation of ignition temperature with longer fuel contact times (>3 sec), which is more appropriately determined in heated-vessel type autoignitions, was not investigated. If the fluid ignited within the 3-second time period, the target temperature was reduced until no ignition was observed within the same time period at a temperature of approximately 30 degrees (°F) below the lowest ignition point. This procedure was repeated using various fuel flow rates. The ignition temperature was defined as the temperature midway between the lowest ignition point and the highest nonignition point. Figure 3 shows a typical ignition that was obtained with the JP-4 jet fuel under flow conditions (1.1 ft/sec). In most cases, the ignition temperature dependency upon air velocity was not investigated above 1200°F because of target temperature limitations. With this limitation, the data were obtained at air velocities up to 8.5 ft/sec depending on the particular fluid-target combination. The determinations were made at air stream temperatures of 80° ± 10°F and 350° ± 20°F.

RESULTS AND DISCUSSION

Although there was no attempt to determine a functional relationship between fuel flow rate and ignition temperature, the ignition temperatures were determined at fuel flows which yielded a minimum value. Figure 4 shows some typical data on the effect of the fuel flow rate on the ignition temperatures of JP-4 and JP-8 jet fuels with the 2-inch diameter by 12-inch long cylindrical target. As noted, their minimum ignition temperatures at an air velocity of 1.7 ft/sec occurred at a fuel flow rate of about 0.02 lb/sec; fuel flow rates of this order were also optimum for ignition of the other fluids that were investigated. Calculated fuel-air weight ratios are also indicated in figure 4, assuming the fuels were completely vaporized and uniformly dispersed; however, they are not necessarily representative of the actual fuel-air ratios at a given location because of the nonuniform fuel distribution expected in these experiments. Generally, the reproducibility of ignition temperature was within ±30°F under most of the experimental conditions.

1. Ignition Temperatures With Cylindrical Targets

The ignition temperatures of five aircraft fluids (JP-4 and JP-8 fuels, MIL-L-7808 engine oil, and MIL-H-5606 and MIL-H-83282 hydraulic fluids) were determined as a function of air velocity and target size in the 8-inch diameter flow tube. Table II summarizes data obtained at air flow temperatures of 80° and 350°F for four of the flammable fluids using 12-inch long cylindrical targets of 1, 2, and 4-inch diameter. Irrespective of the particular target used, it was found that ignition temperatures generally

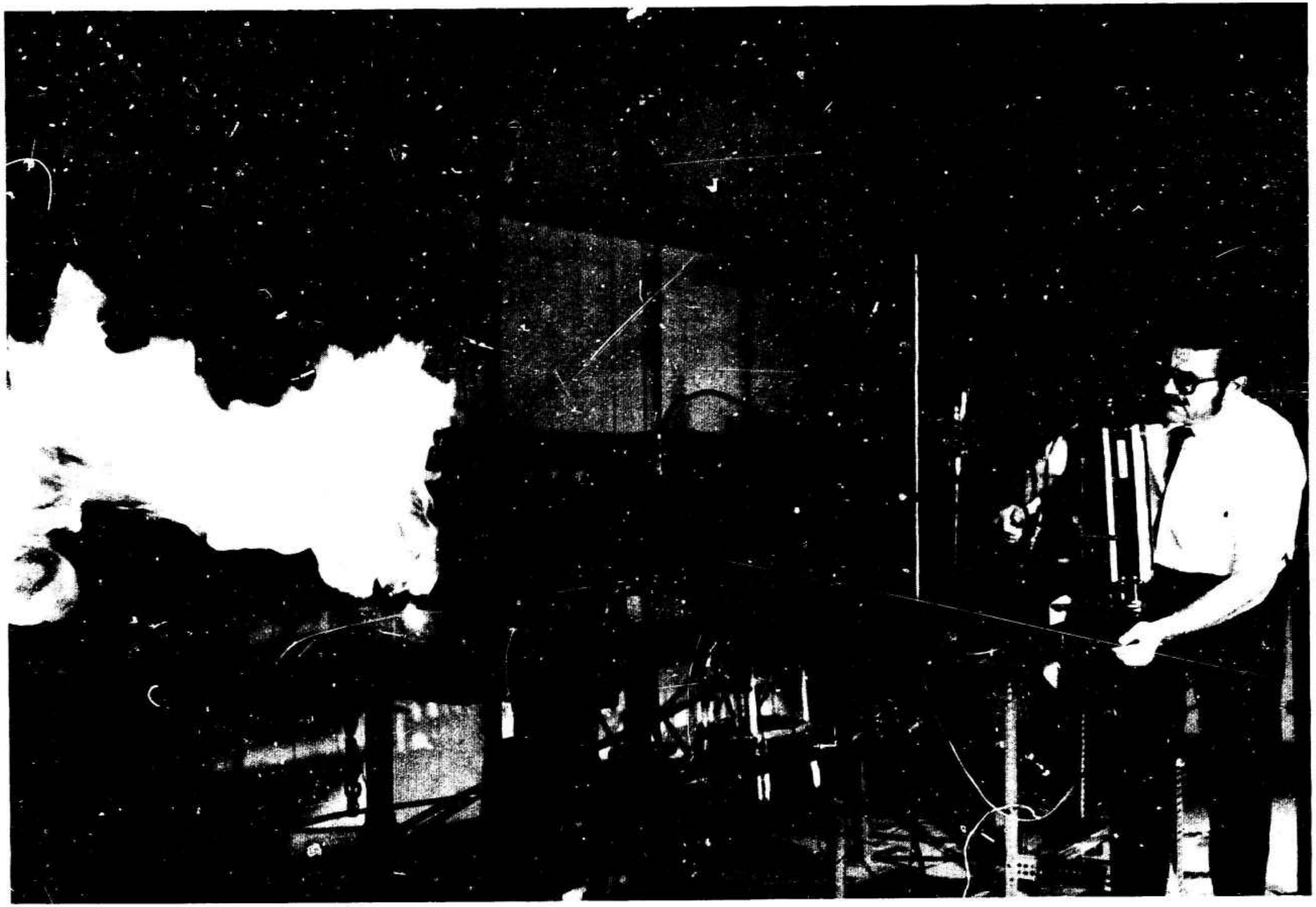


FIGURE 3. - Ignition of JP-4 fuel under flow conditions

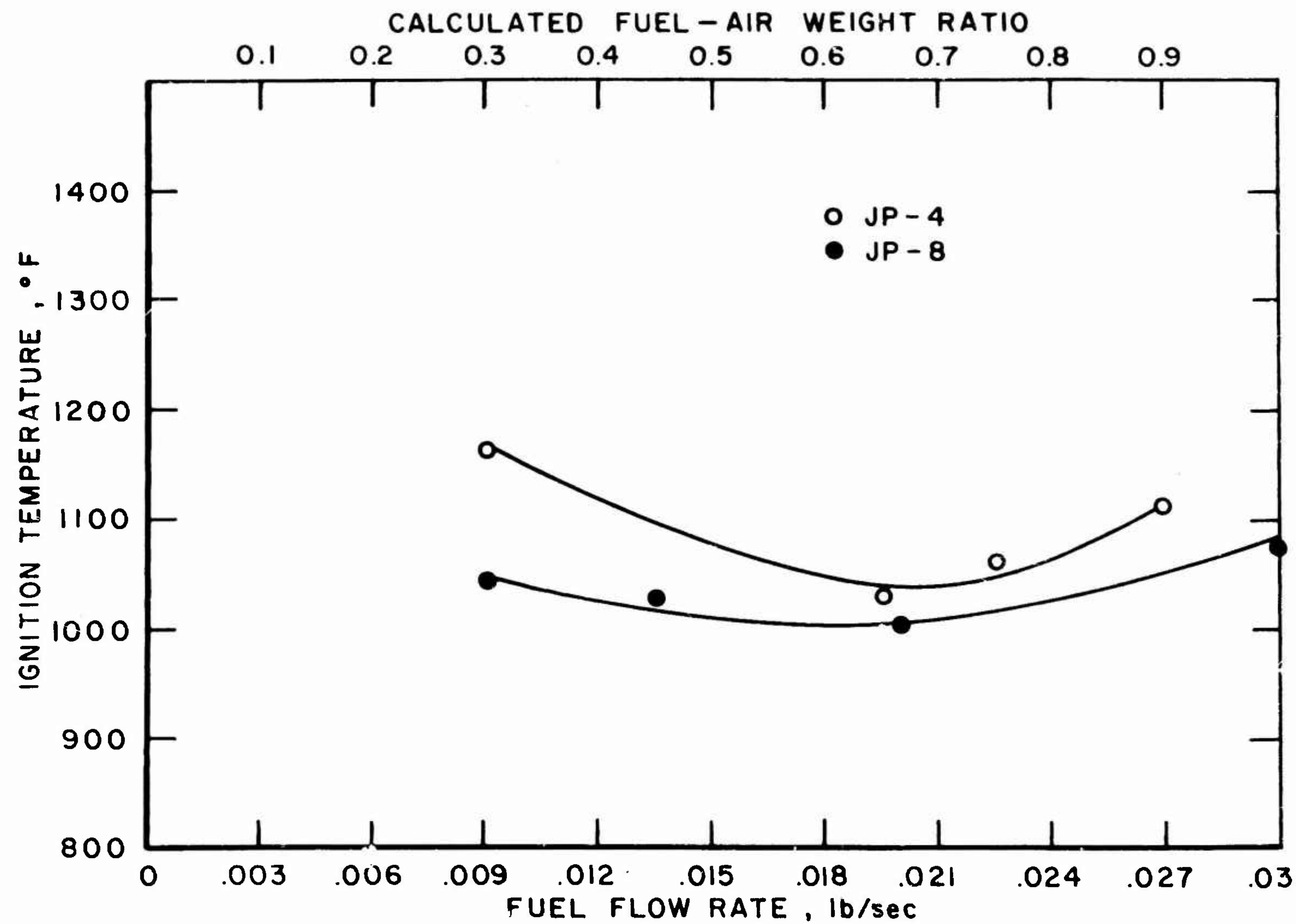


Figure 4. Effect of fuel flow rate on ignition temperatures of JP-4 and JP-8 fuels at an air velocity of 1.7 ft/sec and air temperature of 350°F. Target: 2-inch diameter by 12-inch long.

TABLE II - Ignition Temperatures of Aircraft Fluids Under Various Flow Conditions With 12-inch Long Heated Stainless Steel Targets in an 8-inch Diameter Flow Tube.

Target Diameter (inches)	Air Temperature (°F)	Air Velocity (ft/sec)	Ignition Temperature (°F)
JP-4 Fuel			
1	80	0	1160
		1.1	1180
		2	1190
		3	1230
		6	>1230
2	80	0	1010
		2	1080
		3	1070
		4.5	1090
		6	1140
		8.5	>1200
2	350	0	1010
		1.1	1030
		2	1010
		3	1010
		6	1120
		8.5	1180
4	80	0	920
		1.1	940
		2	960
		3	980
		6	1040
		8.5	1140

Target Diameter (inches)	Air Temperature (°F)	Air Velocity (ft/sec)	Ignition Temperature (°F)
JP-8 Fuel			
1	80	0	1090
		1.1	1220
		2	1250
1	350	1.1	1070
		2	1160
		3	1250
2	80	0	1020
		1.1	1040
		2	1070
		3	1180
2	350	1.1	990
		2	1010
		6	1060
		8.5	1080
4	80	0	900
		1.1	930
		2	980
		3	960
		6	1040
		8.5	1090

TABLE II(Cont'd)

Target Diameter (inches)	Air Temperature (°F)	Air Velocity (ft/sec)	Ignition Temperature (°F)
MIL-L-7808 Engine Oil			
1	80	0	1230
		1.1	>1250
1	350	0	1200
		1.1	1220
		2	>1240
2	80	0	1170
		1.1	1180
		2	1200
		3	>1200
2	350	0	1160
		1.1	1160
		2	1170
		3	1180
		4	>1200
4	80	0	1010
		1.1	1030
		2	1060
		3	1060
		6	1120
		8.5	>1200
4	350	1.1	960
		2	940
		3	1020
		6	1100
		8.5	1130

Target Diameter (inches)	Air Temperature (°F)	Air Velocity (ft/sec)	Ignition Temperature (°F)
MIL-H-5606 Hydraulic Fluid			
1	80	0	1120
		1.1	1170
		2	>1200
1	350	0	1120
		1.1	1220
2	80	0	1070
		1.1	1130
		2	1150
		3	1180
		6	>1200
2	350	0	1070
		1.1	1110
		2	1070
		3	1080
		6	>1200
4	80	0	960
		1.1	960
		2	930
		3	950
		6	1120
		8.5	>1200

increased with increasing air velocity at both air flow temperatures. Moreover, the data indicate that relatively low air velocities can prevent ignition of the fluids despite rather high target temperatures. This behavior is consistent with the conclusions of Goodall and Ingle (Ref 1), who have pointed out that "the risk of spontaneous ignition in any given application is determined by the temperature of a critical volume of mixture rather than by a hot surface temperature and that the surface temperature is a controlling factor only insofar as it affects the temperature of any inflammable mixture." Thus, if the air velocity or ventilation rate is too high, a critical volume of (flammable) mixture is not formed or cannot be heated to a sufficiently high temperature to produce ignition. Even at zero air velocity, the target temperatures required for ignition of the various fluids are considerably higher than their minimum autoignition (AIT's), as determined in heated vessels with quiescent air. A comparison of such ignition temperatures is made in table III for the five fluids used in this work.

TABLE III. - Comparison of Ignition Temperatures of Aircraft Fluids in Quiescent Air With Heated Steel Targets and Heated Glass Vessels.

Aircraft Fluid	Heated Steel Target Ignition Temperatures[a] (°F)	Heated Vessel Ignition Temperatures[b] (°F)
JP-4	920	468 (Ref 7)
JP-8	900	440
MIL-H-5606	960	437 (Ref 4)
MIL-H-83282	1080	670
MIL-L-7808	1010	728 (Ref 4)

a/ Ignitions with 4-inch diameter cylindrical targets.
b/ Ignition evidenced by flame in $\geq$13 in.^{3} (213 cc) vessels.

As shown in figures 5 through 9, the ignition temperature vs air velocity curves are generally concave upward, reflecting the increasing difficulty of attaining the critical temperature with increasing velocity. The effect of air velocity on ignition temperature was most pronounced in runs with the smaller size heat sources, such as the 1- or 2-inch diameter by 12-inch long targets. For the JP-4 fuel (figure 5), the ignition temperature with the 1-inch diameter target varied from 1160°F under static conditions to 1230°F at an air velocity of 3 ft/sec; the initial air stream temperature was 80°F and no ignitions were obtained at an air velocity of 6 ft./sec with the target at 1230°F, the maximum temperature used. With

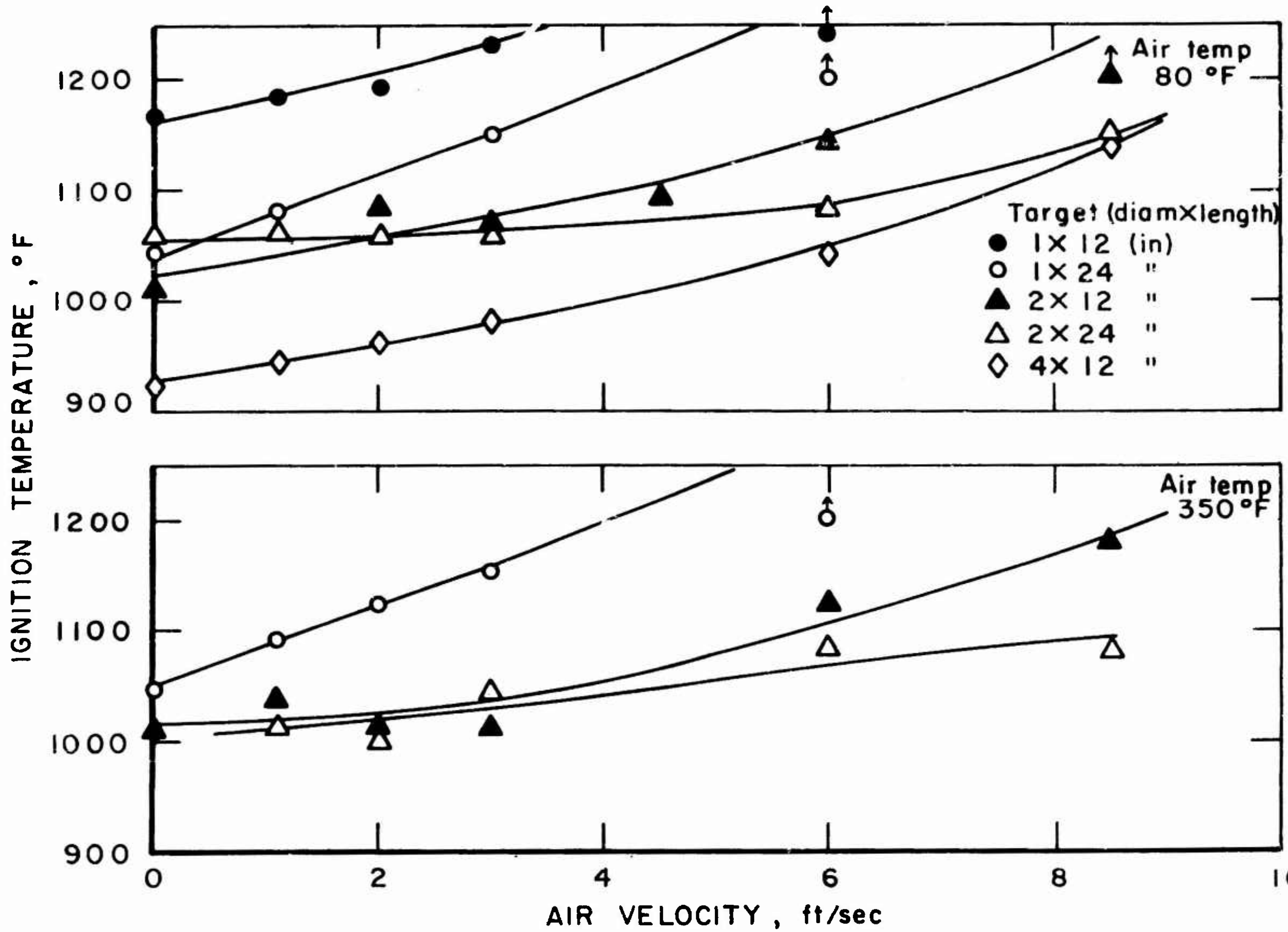


Figure 5. Ignition temperature vs air velocity for JP-4 jet fuel with various heated cylindrical steel targets.

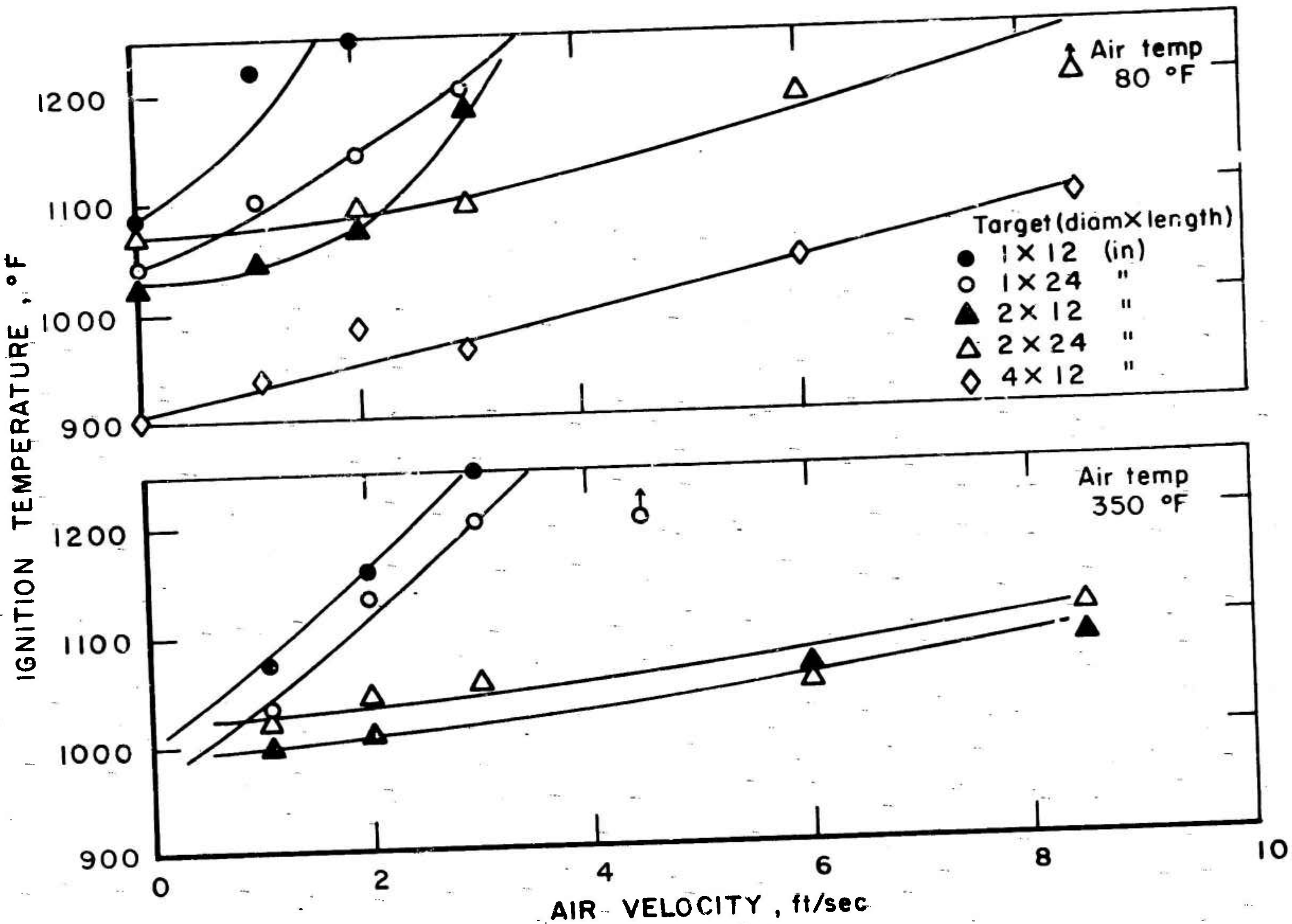


Figure 6. Ignition temperature vs air velocity for JP-8 jet fuel with various heated cylindrical steel targets.

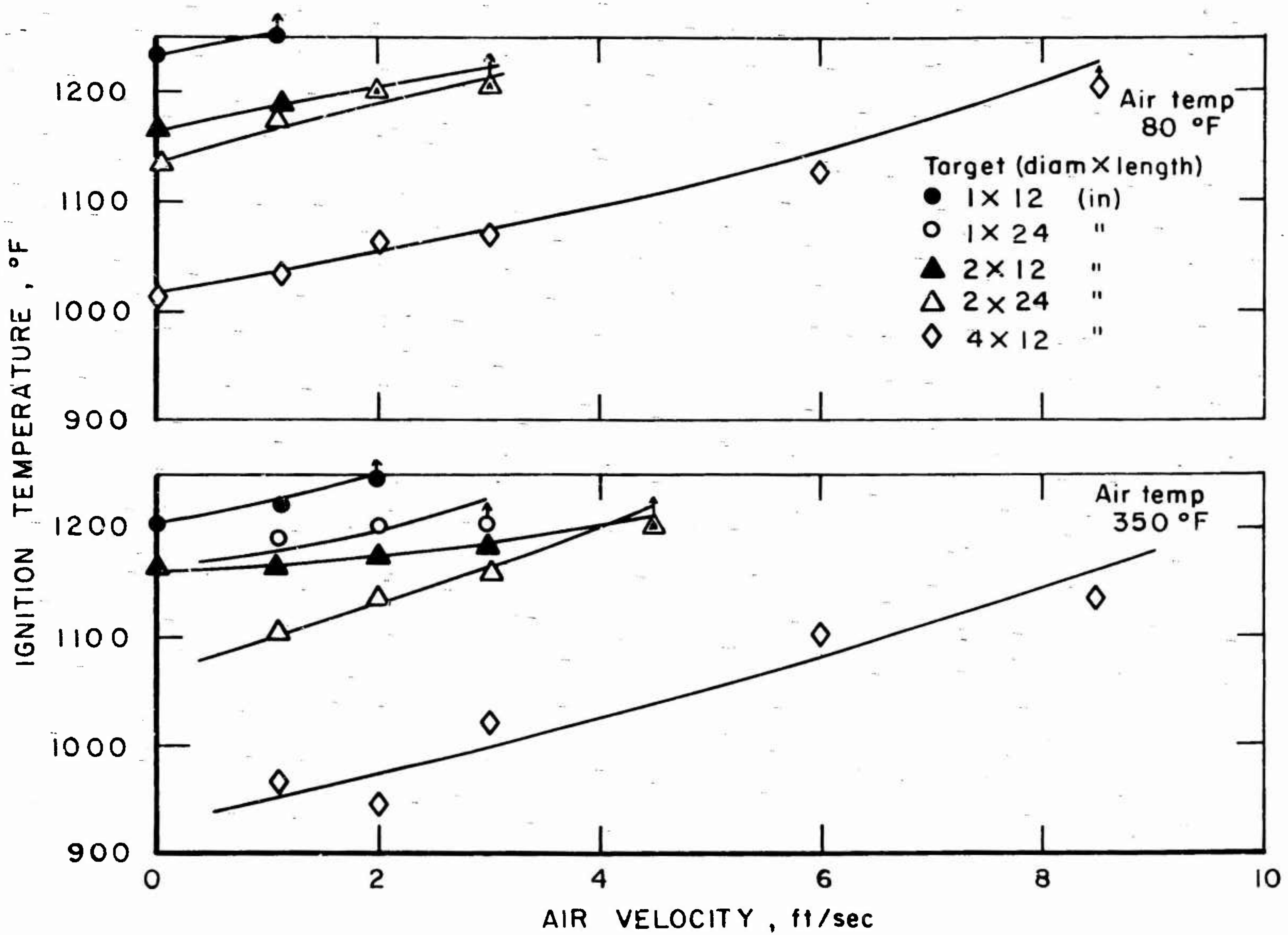


Figure 7. Ignition temperature vs air velocity for MIL-L-7808 engine oil with various heated cylindrical steel targets.

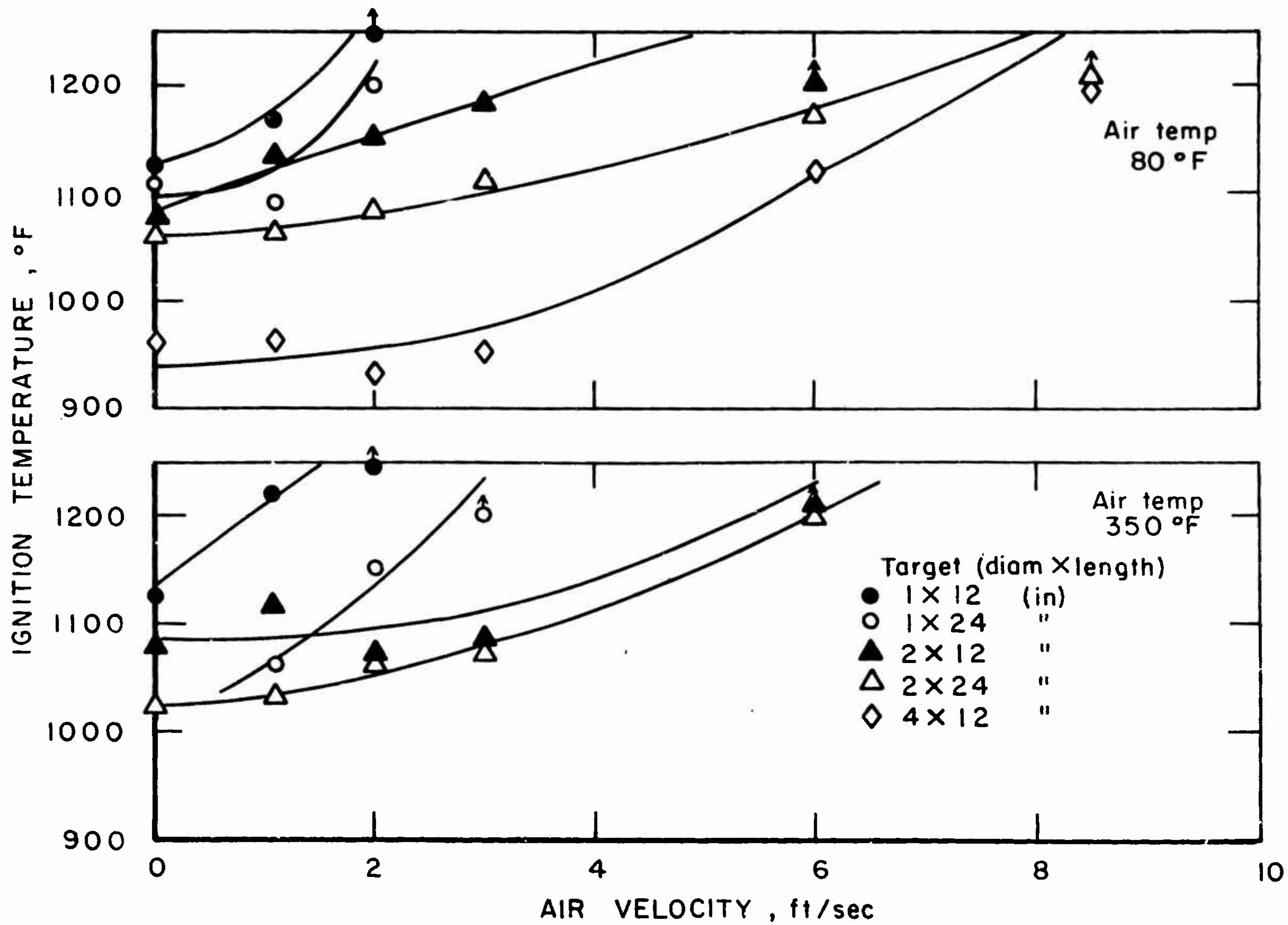


Figure 8. Ignition temperature vs air velocity for MIL-H-5606 hydraulic fluid with various heated cylindrical steel targets.

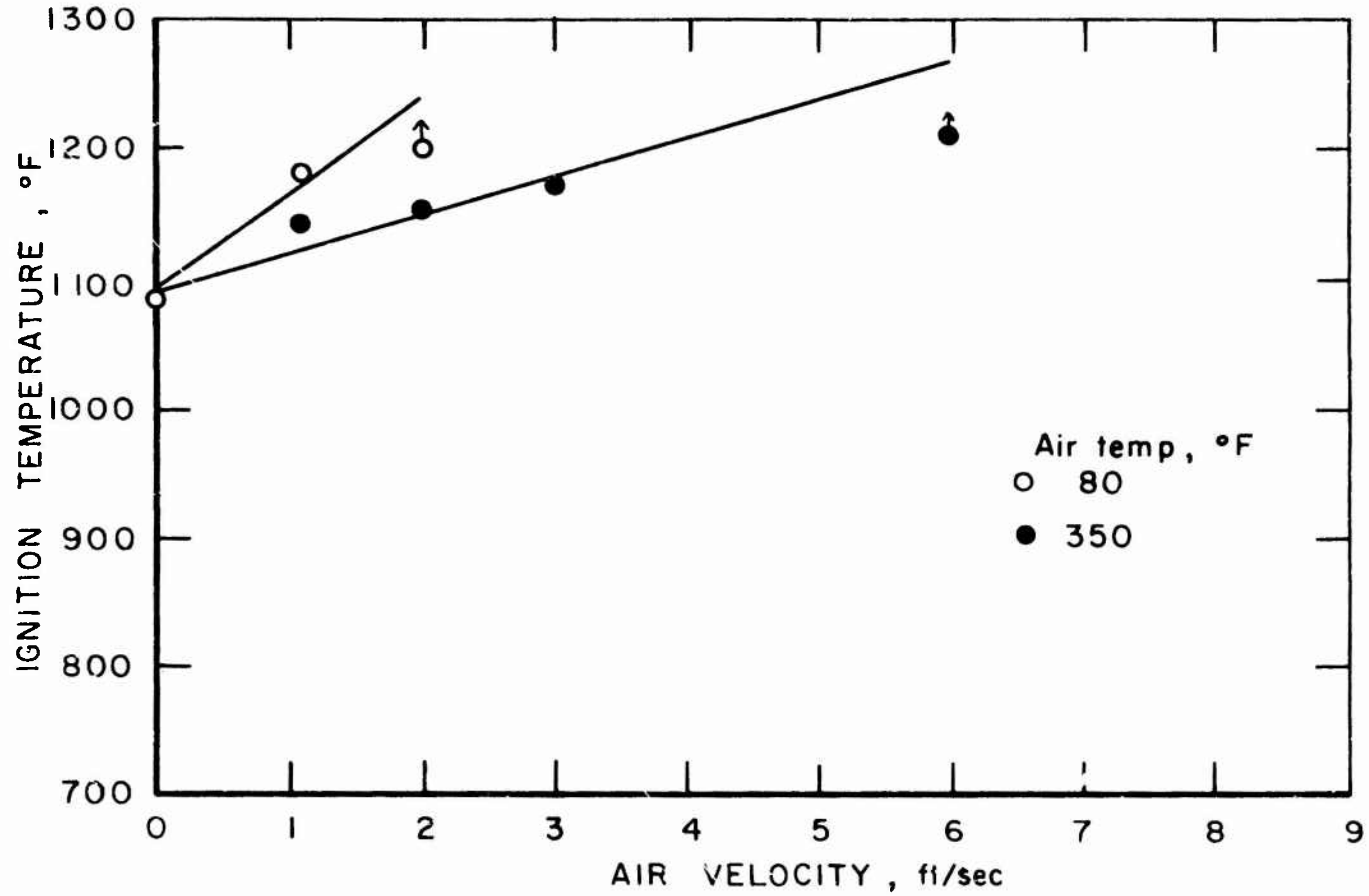


Figure 9. Ignition temperature vs air velocity for MIL-H-83282 hydraulic fluid with a heated 2-inch diameter by 24-inch long steel target.

larger diameter targets of the same length, the ignition temperatures were lower, varying between 1010° and 1150°F for the 2-inch diameter target and between 920° and 1040°F for the 4-inch diameter target at air velocities between 0 and 6 ft./sec. At 8.5 ft./sec (80°F) the JP-4 could not be ignited at 1200°F with the 2-inch diameter target, but ignited at 1140°F with the larger target. Increasing the target length from 12 to 24 inches also caused a lower ignition temperature for JP-4, as shown in figure 5. However, the overall effect of increasing target length was considerably less than that of increasing the diameter. Therefore, in the practical case of the aircraft compartment, the ignition hazard that may result from fuel leakage near a heated pipe or duct can be greater for a short duct of larger diameter than for a longer one of smaller diameter at approximately the same temperature.

The results for the JP-8 fuel, which are shown in figure 6, paralleled those obtained for JP-4. According to these results, differences between the ignition temperature characteristics of the two fuels are small. With the smaller diameter targets, the ignition temperature-air velocity curves were steeper for the less volatile fuel (JP-8) and thus its ignition temperature requirements exceeded the limitations of the equipment at lower velocities than occurred with JP-4. On the other hand, the larger diameter targets tend to ignite the JP-8 and JP-4 fuels at about the same temperatures under the various flow conditions used.

Corresponding data for the fluids with the air preheated to 350°F indicate that the target temperature required for ignition is lower than with the air at room temperature. Although the effect is more marked for low volatility fluids, it is also evident for those of high volatility. For example, with the 2-inch diameter by 12-inch long target at 1200°F, JP-4 could be ignited using preheated air (350°F) at velocities to 8.5 ft./sec, whereas no ignitions were possible with the same air flow at 80°F. This effect of air temperature is not unusual since preheating the air reduces the target heat requirements for the formation and ignition of flammable vapor-air mixtures, and also reduces the severe temperature gradients between the heated target and the walls of the flow tube. Where ignitions were observed at both air flow temperatures, the variation in ignition temperatures was ordinarily less than 100°.

The ignition temperature data for the MIL-L-7808 engine oil (figure 7) and MIL-H-5606 hydraulic fluid (figure 8) displayed air velocity and target size effects similar to those cited for the jet fuels. Highest target temperatures were generally required by the engine oil, which has a much higher minimum AIT than the hydraulic fluid or jet fuels (table III). Ignition temperature values for this high flash point oil (~435°F) were largely above 1100°F with the various targets, except in runs with the 4-inch diameter by 12-inch long target; this was observed at both 80° and 350°F air flow temperatures. The corresponding values for the MIL-H-5606 fluid, which is a high volatility fluid compared to the engine oil, were between

those of the fuels and the engine oil. A few data were also obtained for the MIL-H-83282 hydraulic fluid and these were similar to the MIL-L-7808 data; this new hydraulic fluid has a higher flash point (340°F) and minimum AIT (670°F) than MIL-H-5606. Figure 10 compares the ignition temperatures of these aircraft fluids at various air velocities with a 2-inch diameter by 24-inch long heated target.

2. Ignition Temperatures With Rectangular Targets

In experiments with the flat rectangular target (3-5/8-inch by 12-inch), the ignition temperatures were determined with the target mounted axially in a horizontal plane, and subsequently with the target inclined at an angle of 22-1/2° with the horizontal plane and having the downstream end elevated. The 22-1/2° angle was approximately the maximum inclination possible with the 12-inch long target in the 8-inch diameter flow tube. Figures 11 and 12 summarize the results from these experiments for the two jet fuels and the two hydraulic fluids and engine oil, respectively. As with the cylindrical targets, the ignition temperatures increased with increasing air velocity and were lower when the air was preheated to 350°F. Also, the ignition temperatures for each fluid were consistently lower when the target was in an inclined plane. The lower ignition temperatures with the inclined target are most likely attributed to the longer fuel contact times that should result when the flow is obstructed.

Comparison of the results with cylindrical targets and the rectangular target indicates that the ignition temperatures of JP-4, JP-8, and MIL-H-5606 with a 2-inch diameter by 24-inch long target are approximately equivalent to those found with the 3-5/8-inch by 12-inch flat target in the 22-1/2° inclined plane. However, the results for MIL-L-7808 and particularly MIL-H-83282 with the rectangular target were relatively low compared to those obtained with the above cylindrical target. Although the ignition temperature behavior of such fluids as MIL-L-7808 can be unusual because of their low thermal stability (Ref 4), inconsistencies in the present data could be attributed to nonuniform target temperatures or "hot spots" that were not detected.

The influence of target configuration on ignition temperature was further investigated in a few exploratory experiments with a 2-inch diameter by 12-inch long target equipped with a wire screen. A 2-inch by 2-inch screen (50 mesh) was mounted on a target in such a way as to trap or obstruct the flow of fuel, similar to the condition possible with some aircraft bleed-air lines in the event of a leakage of flammable fluid. Results with the JP-4 fuel indicated that the ignition temperatures were slightly lower with the modified target and comparable to those possible with a 2-inch diameter by 24-inch long target without any screen.

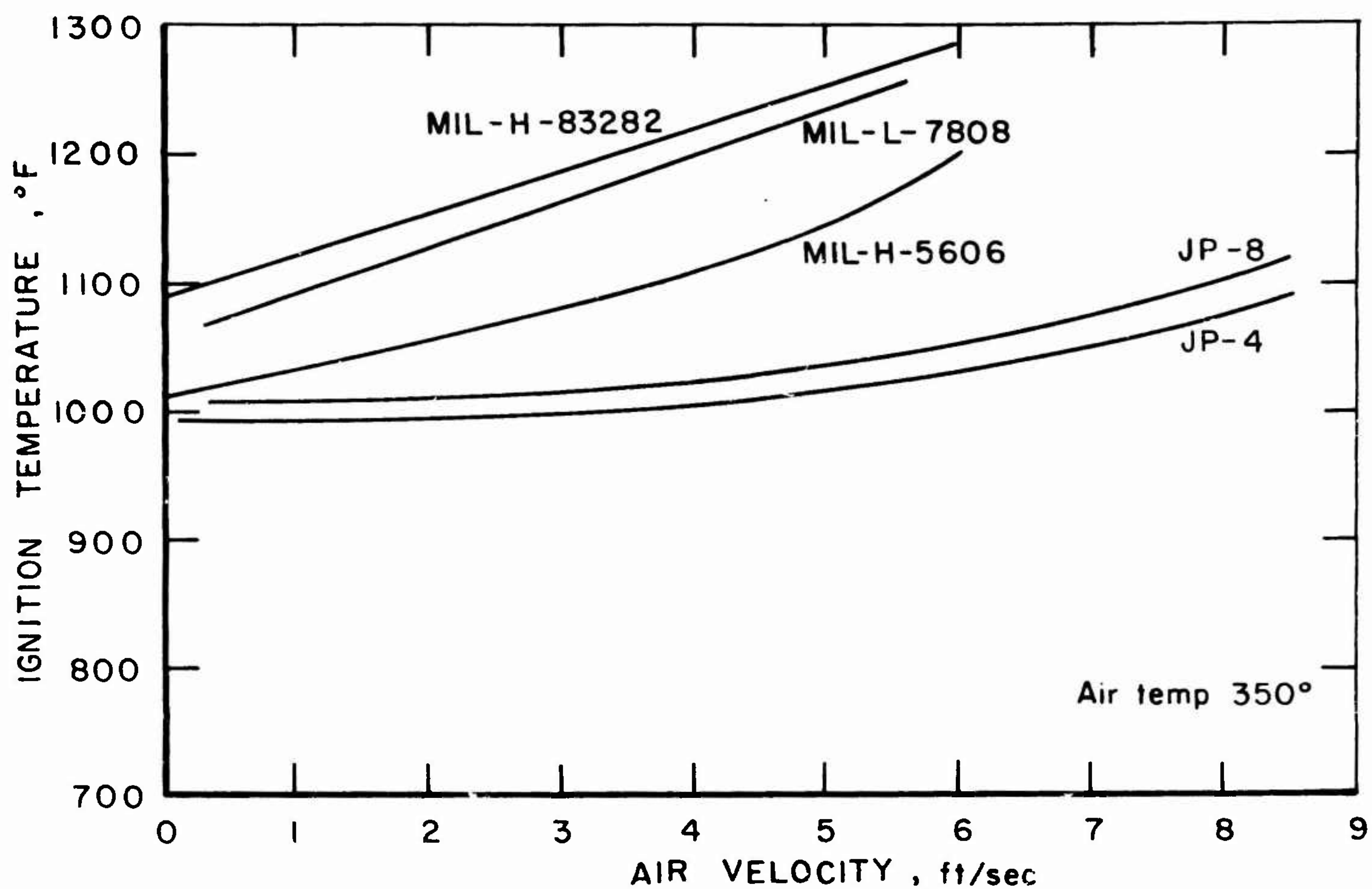


Figure 10. Comparison of ignition temperatures of aircraft fluids at various air velocities with a heated 2-inch diameter by 24-inch long steel target.

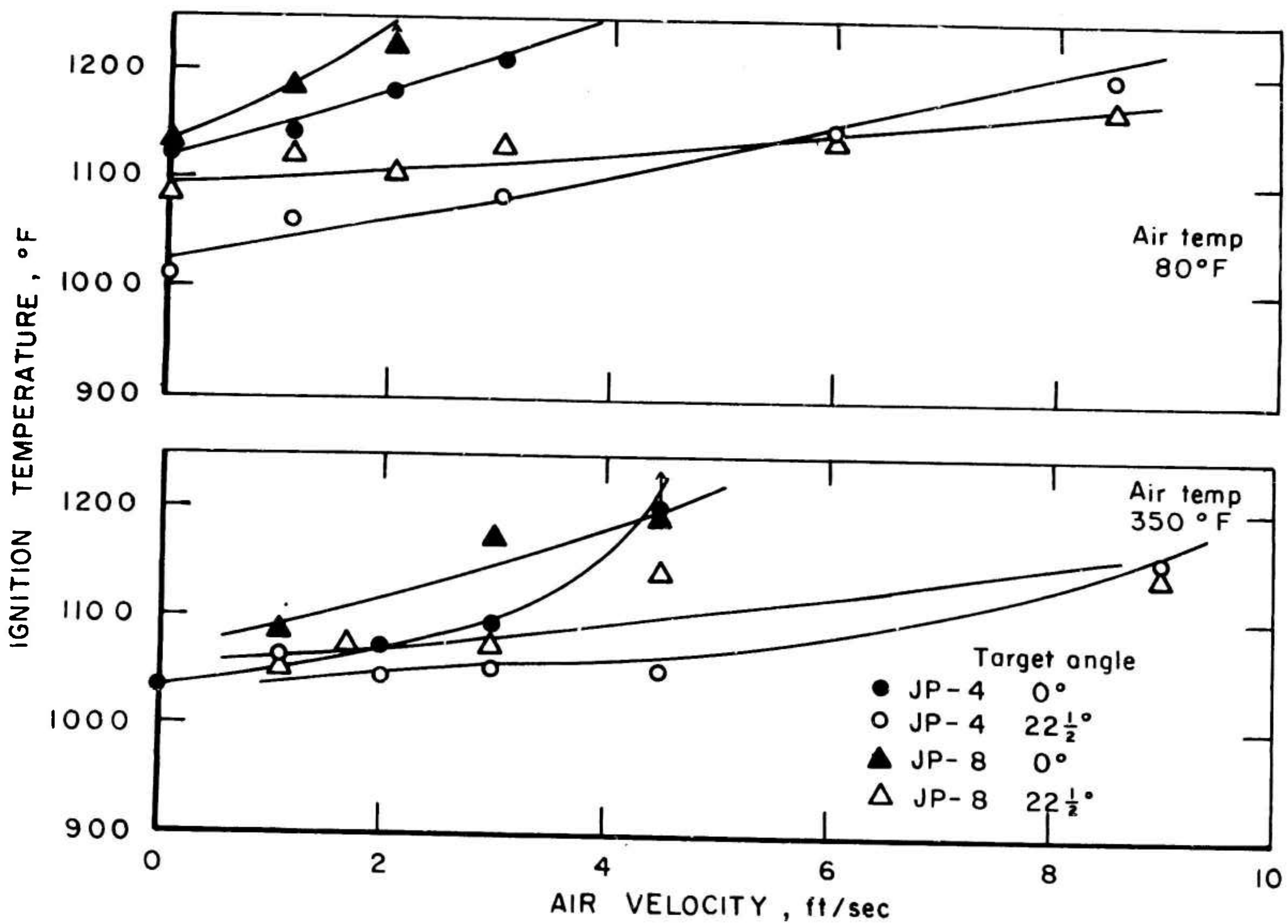


Figure 11. Ignition temperature vs air velocity for JP-4 and JP-8 fuels with a heated 3-5/8-inch wide by 12-inch long steel target.

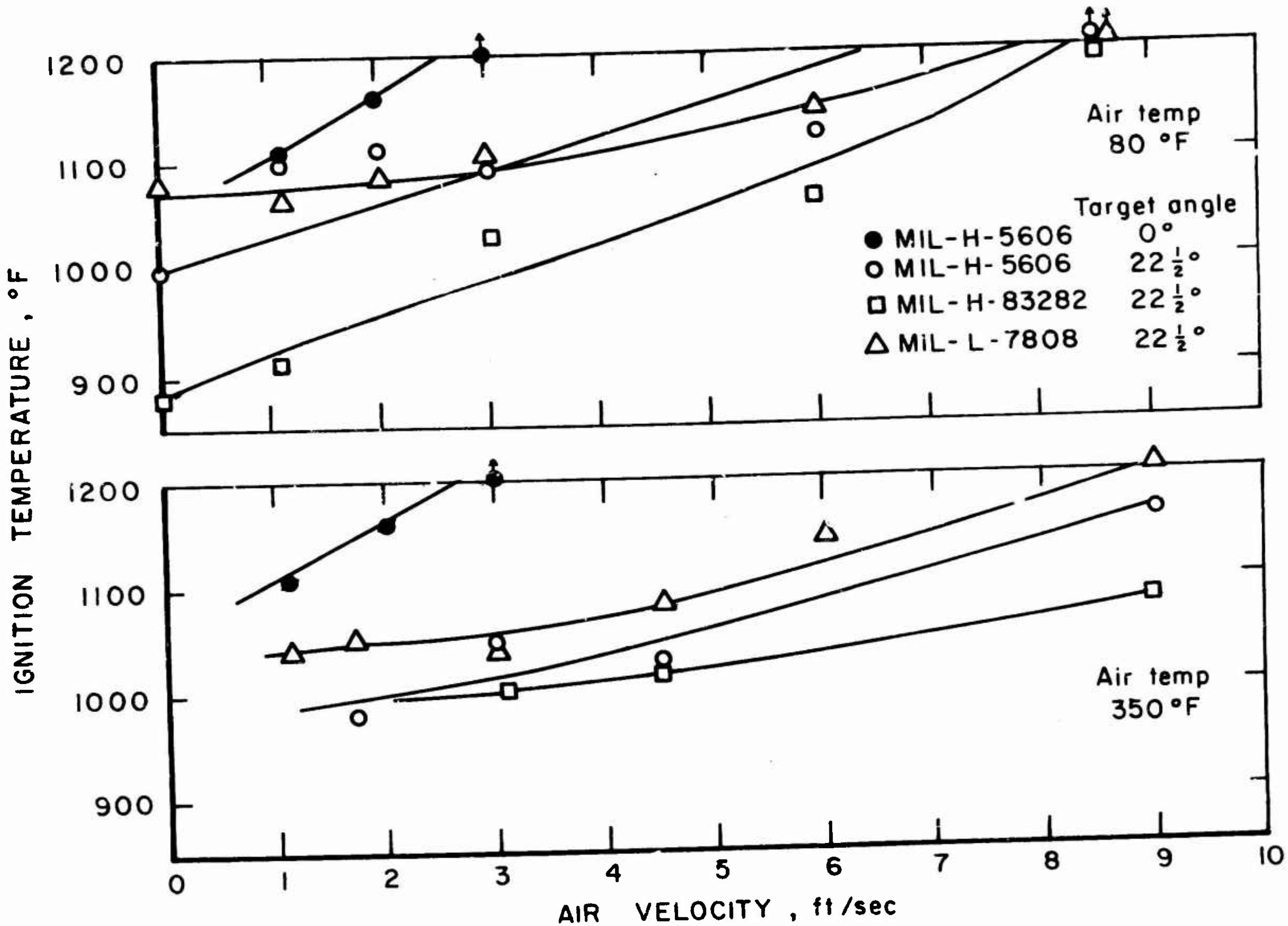


Figure 12. Ignition temperature vs air velocity for MIL-H-5606 and MIL-H-83282 hydraulic fluids and MIL-L-7808 engine oil with a heated 3-5/8-inch wide by 12-inch long steel target.

3. Variation of Ignition Temperature With Fuel Contact Time

Since the ignition temperatures vary with air velocity and target dimensions, it is of interest to correlate these data with fuel contact times, that is, the length of time that the flammable fluid (vapor-air mixtures) contacts the heated target. Fuel contact times for the present experiments were estimated by assuming the fuel particle velocity was equal to the air velocity over the length of the target. Figure 13 shows the variation of ignition temperature of JP-4 with fuel contact time for experiments performed at 350°F air flow temperature with 1-inch and 2-inch diameter targets, 24 inches long. Also included in this figure are previously reported results (Refs 7 and 8) that were obtained for quiescent JP-4 vapor-air mixtures in a 200 cc heated glass vessel and for flowing mixtures in a 2-inch diameter by 36-inch long heated steel tube; the flow tests were made under uniform heating conditions at air velocities from 2 to 22 ft/sec with saturated mixtures (bottom curve) which ignited outside the tube and unsaturated mixtures (top curve) which ignited inside the tube. As noted, the fuel contact times in the present experiments were less than 1 second and the corresponding ignition temperatures, particularly with the 2-inch diameter target, were of the order of those determined with unsaturated mixtures in the 2-inch diameter steel tube. However, the target ignition temperature data displayed a relatively small dependence upon contact time. Data extrapolation to much longer contact times (e.g. 50 seconds) would result in lower ignition temperatures (900-1000°F), but the values would still be much higher than the minimum AIT (468°F) indicated for this fuel; the data shown in figure 5 for JP-4 at zero velocity are consistent in this respect.

Somewhat similar trends were observed in comparing the target ignition temperature data for the MIL-H-5606 hydraulic fluid and MIL-L-7808 engine oil with the heated vessel and flow tube ignition temperature results previously reported for these fluids (Refs 3 and 7). These data are compared in figure 14. Again, extrapolation of the target ignition temperature to long fuel contact times would yield much higher values than the minimum AIT value, in the case of the hydraulic fluid. However, for the engine oil, the difference between these values would be much less because the oil has a high minimum AIT (750°F). Note in figure 7 that the ignition temperature of this oil at zero velocity can be as low as 920°F, depending upon the target size.

In the present experiments, an increase in the fuel contact time or ignition delay permitted a greater buildup of flammable fuel vapor-air mixtures, resulting in more violent ignitions. The severity of these ignitions as a function of ignition delay was recently investigated by Klueg and Demaree (Ref 2) in a full-scale turbofan installation with various aircraft combustible fluids; results of this investigation are also discussed by Westfield (Ref 6).

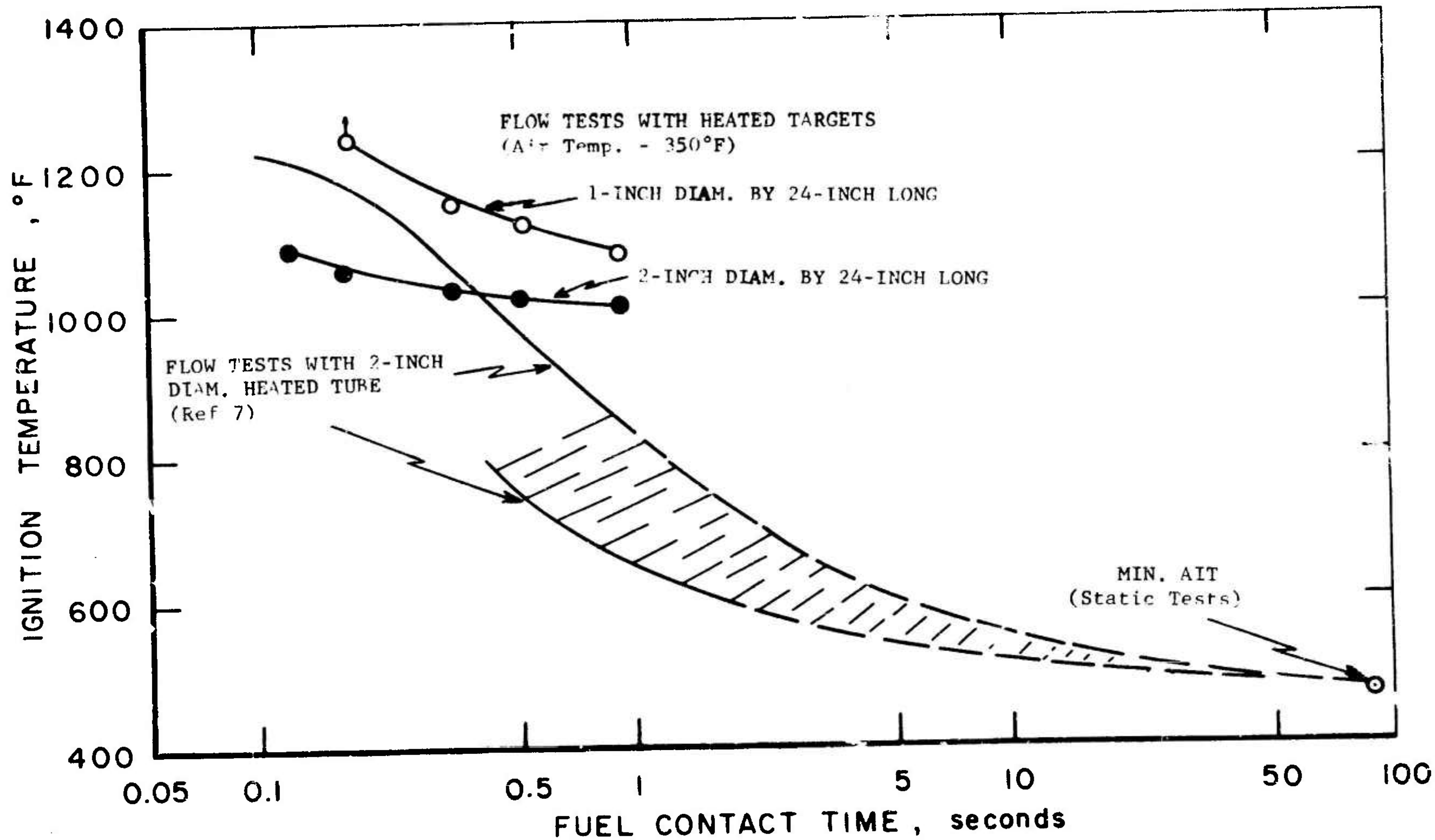


Figure 13. Variation of ignition temperature with fuel contact time for JP-4 jet fuel under static and flow conditions.

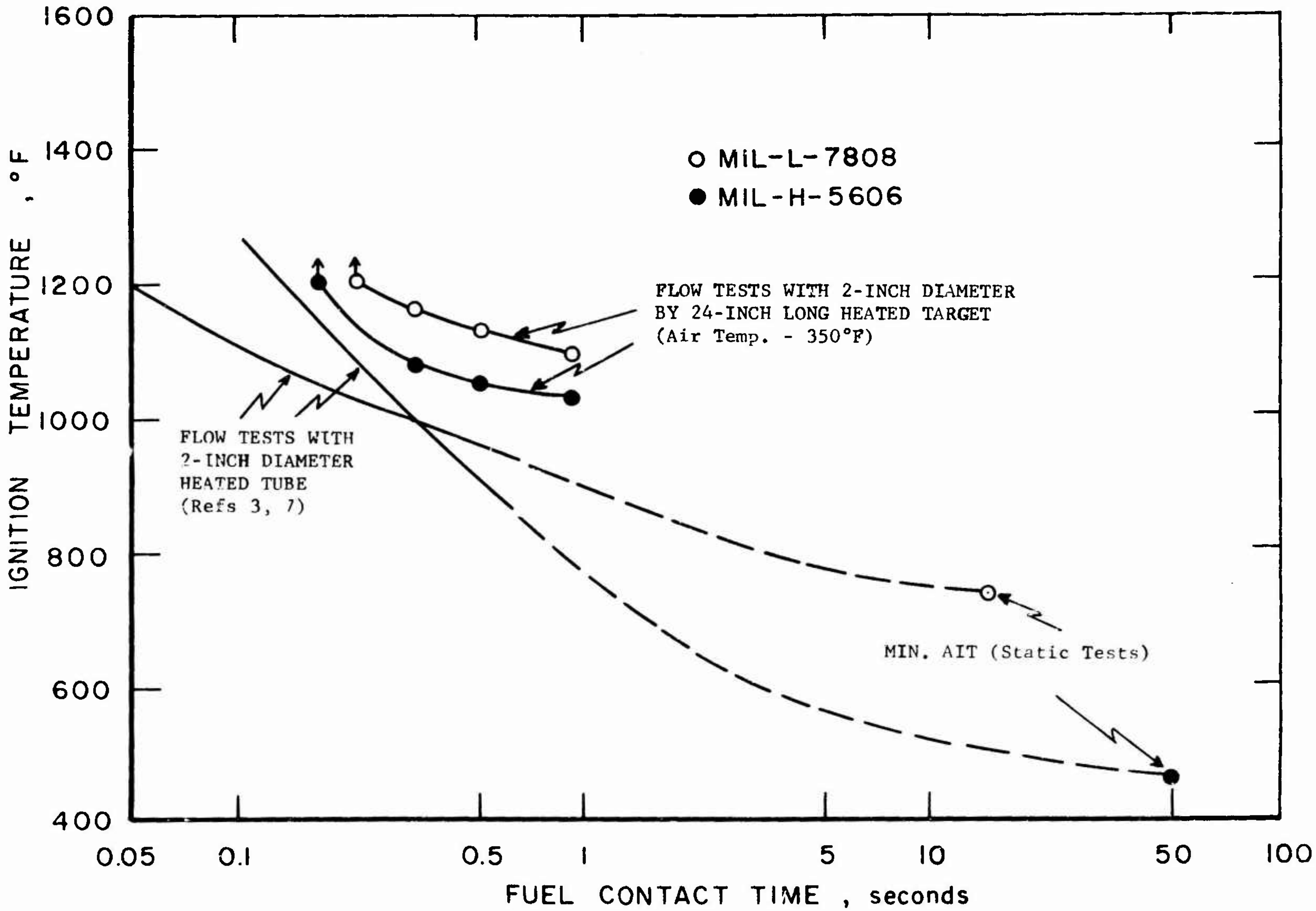


Figure 14. Variation of ignition temperature with fuel contact time for MIL-H-5606 and MIL-L-7808 fluids under static and flow conditions.

4. Correlation of Ignition Temperature With Target Size

The general dependence of ignition temperature upon heat source dimensions is predictable from thermal ignition theory and has been defined for various hydrocarbon fuels with stagnant or near-stagnant vapor-air mixtures (<1 in./sec) that were ignited using heated wires, rods, and vessels (Ref 5). As in the experiments with heated Nichrome wires and rods, (0.16 and 1.0 inch diameter), the ignition temperature data from the present study displayed a moderate dependence upon the heat source diameter. Figure 15 shows the variation of ignition temperature with target diameter at an air velocity of 2 ft/sec (80°F) for four of the aircraft combustible fluids investigated in this work. Data (averaged) from runs with the 12-inch long cylindrical target are used here because they were more complete on diameter effect than those obtained with the 24-inch long target. Similar trends would be expected for the fluids at higher air velocities with the curves being displaced toward higher ignition temperatures.

The curves in figure 15 can be described by an empirical expression, $T_{ign} = kd^n$, where T_{ign} is ignition temperature (°R), $\underline{d}$ is target diameter of 1 to 4 inches, and $\underline{k}$ and $\underline{n}$ are constants which depend upon the combustible fluid and can vary with the target configuration and flow conditions. For the JP-4 and JP-8 fuels, $\underline{n}$ is approximately equal to -0.12 and $\underline{k}$ is 1660 and 1680 respectively; for the MIL-L-7808 and MIL-H-5606 fluids, the corresponding values are approximately -0.14 and -0.17 for $\underline{n}$ and 1800 and 1825 for $\underline{k}$, respectively. Surprisingly, the ignition temperature dependence upon target diameter for the jet fuels was comparable to that indicated by the wire or rod ignition temperature data reported for the JP-6 jet fuel with uniform vapor-air mixtures under near-stagnant conditions (Ref 5). However, in comparing similar sets of data for the MIL-L-7808 fluid, the diameter effect was somewhat greater in the present experiments, although the ignition temperature values in both studies did not differ greatly when compared at the same heat source diameter (1 inch) and practically the same flow conditions (~0 ft/sec); the ignition temperatures under such conditions tended to be about 100° to 200° lower in the experiments with Nichrome rods and uniform test mixtures. In comparison, the diameter effect on the ignition temperatures of the fluid vapor-air mixtures in uniformly heated vessels is not expected to be as great as that observed here with the heated targets. Data cited by Goodall and Ingle show that the minimum AIT of a kerosine fuel in air varies less than 100° when the vessel diameter is varied from 1 inch to 18 inches (Ref 1).

An attempt was also made to correlate the ignition temperature data with the target area, as shown in figure 16. Data were averaged for JP-4, JP-8, and MIL-H-5606 fluids from runs made with the 12- and 24-inch long cylindrical targets and with the 3-5/8-inch by 12-inch flat target; the air velocity was 2 ft/sec and the air flow temperature was 80°F. It is evident from this figure that the ignition temperature dependence upon target area varies with the target length. For example, although a 2-inch diameter by 24-inch long

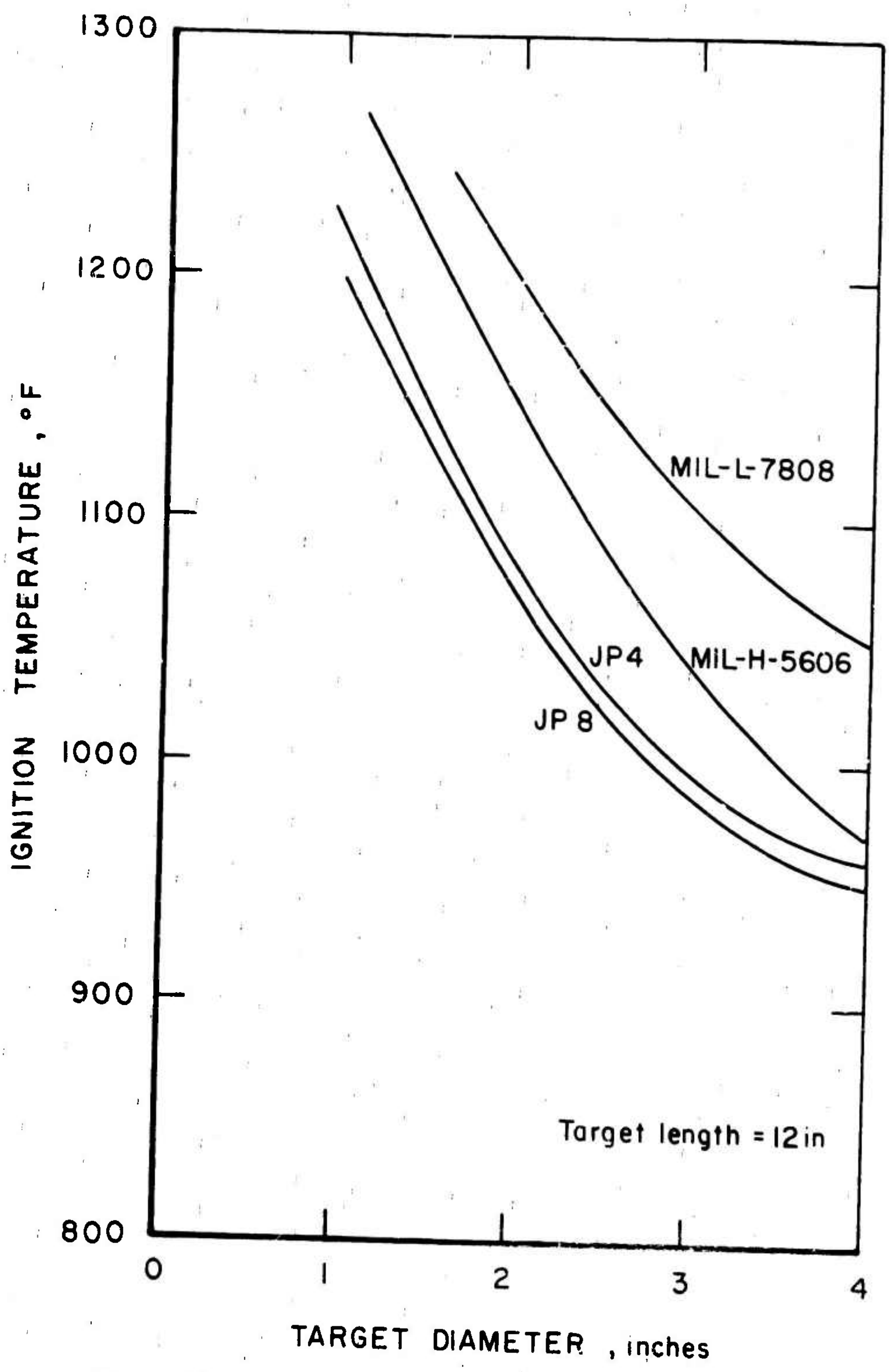


Figure 15. Ignition temperature vs target diameter for various aircraft fluids at air velocity of 2 ft/sec and air temperature of 80°F.

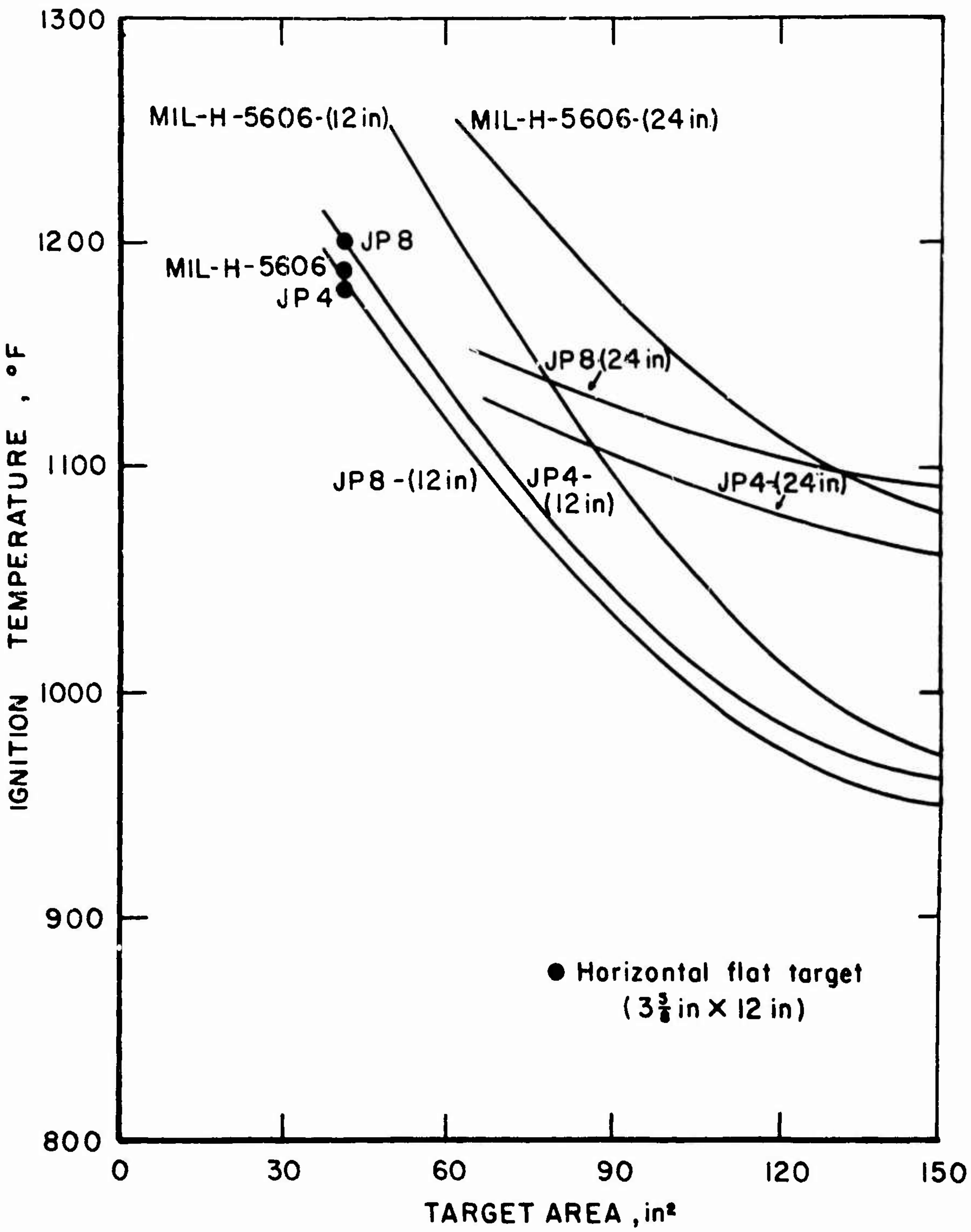


Figure 16. Ignition temperature vs target area for various aircraft fluids with cylindrical targets at air velocity of 2 ft/sec and air temperature of 80°F.

target has the same surface area (150 in.^{2}) as a 4-inch diameter by 12-inch long target, the former consistently gave higher ignition temperatures. Similarly, the 1-inch diameter by 24-inch long target gave higher ignition temperatures than the 2-inch diameter by 12-inch long target, both of which have the same surface area (75 in.^{2}). This trend is evident for all the test fluids at various air velocities from the data in figures 5 through 9. It is further noted in figure 16 that the flat target values for JP-4 and JP-8 are compatible with the ignition temperature-surface area correlations indicated for these fuels with 12-inch long cylindrical targets; however, the same consistency was not necessarily observed in correlating the flat and cylindrical target data of the other combustible fluids, including the MIL-H-5606 hydraulic fluid. Generally, it appears that for long cylindrical targets such as those used in the present work, the surface area effect on ignition temperature due to target diameter variation is much greater than that from target length variation.

CONCLUSIONS

The ignition temperatures of five aircraft combustible fluids investigated with heated metal targets increased th increasing air velocity and depended significantly on factors such as the air flow temperature, target dimensions, and target configuration. Elevated air temperature (350°F) had a greater effect on the results for low volatility fluids than for those of high volatility. At most experimental conditions, the highest ignition temperatures were obtained with the MIL-L-7808 engine oil and MIL-H-83282 hydraulic fluid and the lowest values with the JP-4 and JP-8 jet fuels; the MIL-H-5606 hydraulic fluid tends to give intermediate values.

With cylindrical targets, the ignition temperatures consistently decreased with increasing target diameter (1 to 4 inches). However, the ignition temperature dependence upon target diameter was not pronounced and was of the same order as that previously found with heated wires and rods using uniform hydrocarbon fuel vapor-air mixtures under near-stagnant conditions. Generally, there was no simple correlation with target surface area, because increased target length has a lesser effect than increased diameter. The target ignition temperatures were about the same magnitude as those found for the fluids with vapor-air mixtures flowing in heated tubes at comparable fuel contact times; also, the values at zero air velocity were noticeably higher than the minimum AIT's of the combustible fluids. With a rectangular heated target (3-5/8-inch by 12-inch), the ignition temperatures tended to approximate those with a 2-inch diameter by 24-inch long cylindrical target. The ignition hazard can be expected to increase when heated surfaces are covered such that the flammable fluid is trapped, or if the surface is oriented so that the fuel contact time will be increased.

RECOMMENDATIONS

The following items are recommended for future work:

(1) Prepare a fire safety manual for use in investigating aircraft accidents and in assessing fire and explosion problems associated with aircraft combustibles. The m nual should provide compilations of pertinent ignition and flammability data, as well as useful guidelines for defining hazardous conditions, for analyzing fire and explosion damage, and for investigating aircraft accidents. Fire hazard properties of liquid, solid, and gaseous combustibles should be included, together with information on reducing the fire or explosion hazards.

(2) Determine ignition and flammability properties of aircraft combustibles submitted for evaluation, including those for which such information is currently lacking.

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